

# New limits on radiative sterile neutrino decays from a search for single photons in neutrino interactions.

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## Abstract

It has been recently shown that excess events observed by the LSND and Mini-BooNE neutrino experiments could be interpreted as a signal from the radiative decay of a heavy sterile neutrino  $\nu_h$  produced in  $\nu_\mu$  neutral current-like neutrino interactions. If the  $\nu_h$  exist, it would be also produced by the  $\nu_\mu$  beam from the CERN SPS in the neutrino beam line shielding. The  $\nu_h$ 's would penetrate the shielding and be observed through the  $\nu_h \rightarrow \gamma\nu$  decay followed by the photon conversion into  $e^+e^-$  pair in the active target of the NOMAD detector. The  $\nu_h$ 's could be also produced in the iron of the magnetic spectrometer of the CHORUS detector, located just in front of NOMAD. Considering these two sources of  $\nu_h$ 's we set new constraints on  $\nu_h$  properties and exclude part of the LSND/MiniBooNE  $\nu_h$  parameter space using bounds on single photons production in neutrino reactions recently reported by the NOMAD collaboration. We find that broad bands in the parameter space are still open for more sensitive searches for the  $\nu_h$  in future neutrino experiments.

*Key words:* neutrino mixing, neutrino decay

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Over the past 10 years there is a puzzle of the  $3.8\sigma$  event excess observed by the LSND collaboration [1]. This excess originally interpreted as a signal from  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations was not confirmed by further measurements from the similar KARMEN experiment [2]. The MiniBooNE experiment, designed to examine the LSND effect, also found no evidence for  $\nu_\mu \rightarrow \nu_e$  oscillations. However, an anomalous excess of low energy electron-like events in quasi-elastic neutrino events over the expected standard neutrino interactions has been observed [3]. Recently, MiniBooNE has reported new results from a search for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations [4]. An excess of events was observed which has a small probability to be identified as the background-only events. The data are found to be consistent with  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations in the  $0.1\text{ eV}^2$  range and with the evidence for antineutrino oscillations from the LSND.

In the recent work [5] (see also [6,7,8]) it has been shown that these puzzling results could all be explained in a consistent way by assuming the existence of a heavy sterile neutrinos ( $\nu_h$ ). The  $\nu_h$  is created in  $\nu_\mu$  *neutral-current* (NC) interactions and decay subsequently into a photon and a lighter neutrino  $\nu$  in the LSND and MiniBooNE detectors, but it cannot be produced in the KARMEN experiment due to the high energy threshold. The  $\nu_h$  could be Dirac or Majorana type. The  $\nu_h$  could decay *dominantly* into  $\gamma\nu$  pair if, for example, there is a large enough transition magnetic moment between the  $\nu_h$  and  $\nu$  mass states. Assuming the  $\nu_h$  is produced through mixing with  $\nu_\mu$ , the combined analysis of the LSND and MiniBooNE excess events suggests that the  $\nu_h$  mass, mixing strength, and lifetime are, respectively, in the range

$$40 \lesssim m_h \lesssim 80 \text{ MeV}, \quad 10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2}, \quad 10^{-11} \lesssim \tau_h \lesssim 10^{-9} \text{ s}. \quad (1)$$

A detailed discussion of consistency of these values with the constraints from previous searches for heavy neutrinos [9] is presented in [5]. Briefly, the mixing of (1) is not constrained by the limits from the the most sensitive experiments searched for extra peaks in two-body  $\pi, K$  decays [9,10], because the  $\nu_h$  mass range of (1) is outside of the kinematical limits for  $\pi_{\mu 2}$  decays, and not accessible to  $K_{\mu 2}$  experiments due to experimental resolutions. The parameter space of (1) cannot be ruled out by the results of high energy neutrino experiments, such as NuTeV [11] or CHARM [12,13], as they searched for  $\nu_h$ 's of higher masses ( $m_h \gtrsim 200 \text{ MeV}$ ) decaying into muonic final states ( $\mu\pi\nu, \mu\mu\nu, \mu e\nu, \dots$ ) [9], which are not allowed in our case. The best limits on  $|U_{\mu h}|^2$  derived for the mass range (1) from the search for  $\nu_h \rightarrow e^+e^-\nu$  decays in the PS191 experiment [14], as well as the LEP bounds [15], are found to be compatible with (1) assuming the dominance of the  $\nu_h$  decay. New limits on mixing  $|U_{\mu h}|^2$  obtained by using the recent results on precision measurements of the muon Michel parameters by the TWIST experiment [16] are also found to be consistent with (1). Finally, the most stringent bounds on  $|U_{\mu h}|^2$  coming from the primordial nucleosynthesis and SN1987A considerations, as well as the limits from the atmospheric neutrino experiments, are also evaded due to the short  $\nu_h$  lifetime.

Recently, several constraints on the properties of the  $\nu_h$  obtained from the muon capture on hydrogen [17] and radiative decays of charged kaons [18,19] have been reported. The new bounds, found to be in tension with (1), are obtained under assumption that the  $\nu_h$ , as a component of the  $\nu_\mu$ , could be also produced in reactions induced by  $\nu_\mu$  charge-current (CC) interactions. However, one may argue that the heavy neutrino explanation of the LSND/MiniBooNE anomaly assumes that excess events are originated from the decays of  $\nu_h$ 's produced in a new  $\nu_\mu$  NC-like interactions, i.e. without charge muon emission [5]. Therefore, the constraints of Ref.'s [17,18,19] can be evaded, if e.g. the new fermion  $\nu_h$  has new dominant NC-like interactions, while its CC reactions are suppressed.

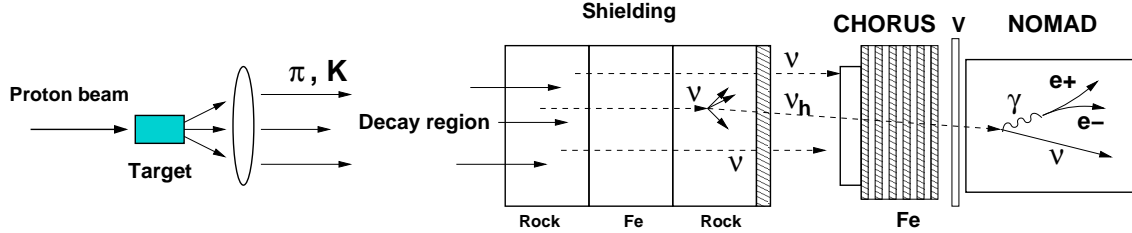


Fig. 1. Schematic illustration of the experiment to search for the  $\nu_h \rightarrow \gamma\nu$  decay of a sterile neutrino. If the  $\nu_h$ 's exist, they would be produced in  $\nu_\mu$  interactions in the CERN WNF  $\nu_\mu$  neutrino beam line shielding. The particles would penetrate the downstream shielding and be observed in the NOMAD neutrino detector through their  $\nu_h \rightarrow \gamma\nu$  decays into a photon and a light neutrino followed by the photon conversion into  $e^+e^-$  pair in the NOMAD target. The shaded region of the shielding serves as a dump of the thickness about  $9 \lambda_{int}$  (interaction lengths) to absorb neutrino shower components which could escape absorption in the CHORUS detector matter, and generate background events in NOMAD.

There are several possibilities for such scenario. For example, the  $\nu_h$  can be produced by the Primakoff conversion,  $\nu_\mu + Z \rightarrow \nu_h + Z$  of the muon neutrino in the electromagnetic field of nuclei due to dipole transition moment between the  $\nu_h$  and  $\nu_\mu$  states, with the subsequent decay  $\nu_h \rightarrow \gamma\nu$  due to the same interaction, see, e.g. Fig. 1 in [20] and, also [21] for more detail discussions. Another mechanisms, we are mostly interested in, adopt new interaction to produce sterile neutrinos in muon neutrino scattering off nuclei. In the standard model, in our case of low energies, both  $Z$ - and  $W$ -boson contributions to neutrino scattering are naturally of the same order, because there is no hierarchy between  $Z$ - and  $W$ -boson masses. Would  $W$ -boson be much heavier, charge current contributions to neutrino scattering off nuclei are suppressed as compared to that of neutral current. Consequently, to diminish the meaning of charge current channel in searches for sterile neutrinos one can involve a similar hierarchy for the new interaction responsible for sterile neutrino production. Such a model based on adding to the SM one new scalar doublet with the same gauge quantum numbers as the SM Higgs field [22] is discussed elsewhere [21]. Similar scenario could arise also in the low-energy superstring-inspired  $E_6$  theories [23]. In all these cases one does not need any sterile-active neutrino mixing at all to explain sterile neutrino appearance in muon neutrino beam traveling through a neutrino detector volume. Therefore, it would be interesting to obtain direct experimental constraints on the such  $\nu_h$  properties.

In this Letter we study new constraints on properties of  $\nu_h$ 's from the measurements of the NOMAD experiment at the CERN WNF neutrino beam, assuming the  $\nu_h$ 's are produced dominantly in new  $\nu_\mu$ NC-like reactions. The present analysis as well as the experimental signature of the signal events are similar to those of heavy neutrino searches previously reported in [24,25,26].

The CERN West Area Neutrino Facility (WANF) beam line [27] provides an essentially pure  $\nu_\mu$  beam for neutrino experiments. It consists of a beryllium target irradiated by 450 GeV protons from the CERN SPS. The secondary hadrons of a given sign are focused with two magnetic elements located in front of a 290 m long evacuated decay tunnel. Protons that do not interact in the target, secondary hadrons and muons that do not decay are absorbed by a 400 m thick shielding made of iron and earth. The NOMAD detector is located at 835 m from the neutrino target. The detector is described in detail in Ref. [28]. It consists of a number of sub-detectors most of which are located inside a 0.4 T dipole magnet with a volume of  $7.5 \times 3.5 \times 3.5$  m<sup>3</sup>: an active target of drift chambers (DC) with a mass of 2.7 tons (mainly carbon), and a total thickness of about one radiation length followed by a transition radiation detector, a preshower detector, and an electromagnetic calorimeter. A hadron calorimeter and two muon stations are located just after the magnet coils. A plane of scintillation counters,  $V$ , in front of the magnet was used to veto upstream neutrino interactions and muons incident on the detector.

If the  $\nu_h$  exists, it would be produced in interactions

$$\nu_\mu + N \rightarrow \nu_h + X. \quad (2)$$

of muon neutrinos in the WANF neutrino beam shielding. If the  $\nu_h$  is a relatively long-lived particle, the flux of  $\nu_h$ 's would penetrate the downstream part of the shielding without significant attenuation and be observed in NOMAD through  $\nu_h \rightarrow \gamma\nu$  decays followed by the decay photons conversion into  $e^+e^-$  pairs in the NOMAD DC target, as schematically illustrated in Fig.1. The experimental signature of  $\nu_h \rightarrow \gamma\nu$  decays would appear as an excess of isolated  $e^+e^-$  pairs above those expected from standard neutrino interactions. As the NOMAD searched for an excess of isolated  $e^+e^-$  pairs in their detector, the results obtained can be also used to constrain the radiative decay of the  $\nu_h$ . Note, that the search for an excess of isolated photon events in neutrino interactions is complicated by the presence of a large background coming from the electromagnetic decays of neutral mesons (mostly  $\pi^0, \eta, \eta' \rightarrow \gamma\gamma$ ). However, because the experimental signature of these events is clean, they can be selected with significantly suppressed background due to the excellent NOMAD capability for precise measurements of  $e^+e^-$  pairs, see for example [24,25,26].

To make quantitative estimates, we performed simplified simulations of the  $\nu_h$  production (2) and decay in the NOMAD detector schematically shown in Fig. 1. The flux of  $\nu_h$ 's produced in the shielding was calculated by using the known flux of  $\nu_\mu$  beam in NOMAD [29]. In these simulation the  $\nu_h$  production vertex was required to be located in the upstream part of the shielding excluding shaded region shown in Fig.1. This end cap region serves as an additional dump to absorb neutrino hadronic shower components, which might escape absorption in the matter of the CHORUS detector located downstream. The

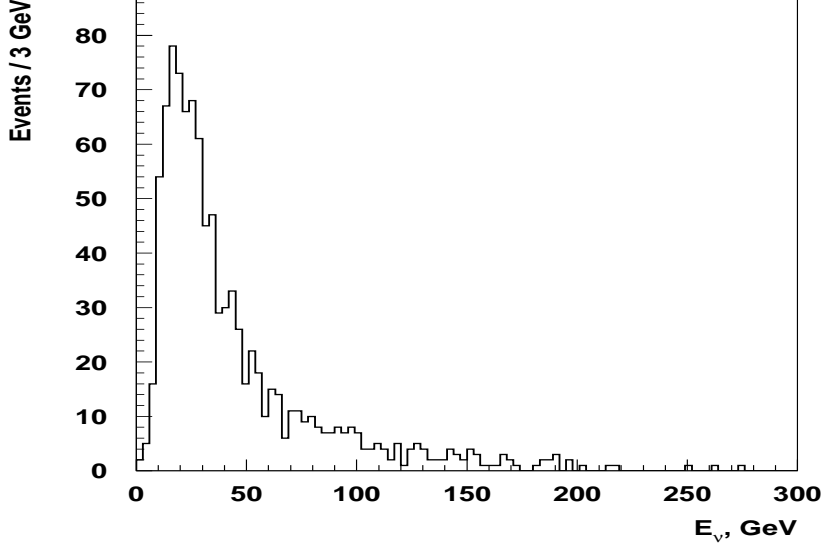


Fig. 2. *Energy spectra of muon neutrinos that produce heavy neutrino with the mass of 50 MeV in neutral current interactions in the WANF neutrino beam line shielding.*

choice of the dump thickness of  $9 \lambda_{int}$  (interaction lengths) allows to fully protect NOMAD from the leak of secondary particles produced in the upstream neutrino interactions, and suppress background from punch-through  $K_L^0$  and  $n$  interactions in NOMAD that could produce fake signal. More accurate analysis would require detailed simulations of the background in the NOMAD detector, which is beyond the scope of this work. Note, however, that obtained limits are not very sensitive to the choice of the dump thickness within the range  $\simeq 9 - 15 \lambda_{int}$ .

The simulated energy spectrum of the incident  $\nu_\mu$ 's is shown in Fig.2. It is assumed that, similar to the case of neutrino mixing, the cross section of heavy neutrinos production (2) can be expressed in a model-independent way as follows:

$$\sigma(\nu_\mu + N \rightarrow \nu_h + X) = \alpha_{\mu h} \sigma(\nu_\mu + N \rightarrow \nu_\mu + X) f_{ph.s.} \quad (3)$$

where  $\sigma(\nu_\mu + N \rightarrow \nu_\mu + X)$  is the cross section for  $\nu_\mu$ NC interactions,  $f_{ph.s.} = \sigma(m)/\sigma(0)$  is the phase space factor which takes into account dependence on the  $\nu_h$  mass, and  $\alpha_{\mu h}$  play a role of an effective coupling strength in new  $\nu_h$ -NC-like interactions. The distribution of energies for  $\nu_h$ 's with momenta pointing to the NOMAD fiducial area, and photons from the isotropic  $\nu_h \rightarrow \gamma\nu$  decay in the NOMAD target are shown in Fig.3. Once the  $\nu_h$  flux was known, the next step was to calculate the  $e^+e^-$  spectrum based on the  $\nu_h \rightarrow \gamma\nu$  decay rate. For a given flux  $\Phi(\nu_h)$ , the expected number of signal events from  $\nu_h \rightarrow \gamma\nu$

decays occurring within the fiducial length  $L$  of the NOMAD detector located at a distance  $L'$  from the  $\nu_h$  production vertex is given by

$$N_{\nu_h \rightarrow \gamma \nu} = \int A \Phi(\nu_h) \exp\left(-\frac{L' m_{\nu_h}}{p_{\nu_h} \tau_h}\right) \left[1 - \exp\left(-\frac{L m_{\nu_h}}{p_{\nu_h} \tau_h}\right)\right] \frac{\Gamma_{\gamma \nu}}{\Gamma_{tot}} P_{\gamma} \varepsilon_{e^+ e^-} dE_{\nu_h} dV \quad (4)$$

where  $p_{\nu_h}$  is the  $\nu_h$  momentum,  $\tau_h$  is its lifetime at the rest frame,  $\Gamma_{e^+ e^-}$ ,  $\Gamma_{tot}$  are the partial and total  $\nu_h$ -decay widths, respectively,  $P_{\gamma}$  is the decay photon conversion probability, and  $\varepsilon_{e^+ e^-}$  is the  $e^+ e^-$  pair reconstruction efficiency. The acceptance  $A$  of the NOMAD detector was calculated tracing  $\nu_h$ 's produced in the shielding to the detector. As an example for a mass  $m_{\nu_h} = 50$  MeV,  $A = 4.8\%$  and  $\varepsilon_{e^+ e^-} \simeq 25\%$ . It is assumed that the total rate  $\Gamma_{tot}$  of the  $\nu_h$  decays is dominated by the radiative decay  $\nu_h \rightarrow \gamma \nu$ , see discussion in [5], hence the branching fraction of the  $\nu_h \rightarrow \gamma \nu$  decay is  $BR(\nu_h \rightarrow \gamma \nu) = \frac{\Gamma(\nu_h \rightarrow \gamma \nu)}{\Gamma_{tot}} \simeq 1$ .

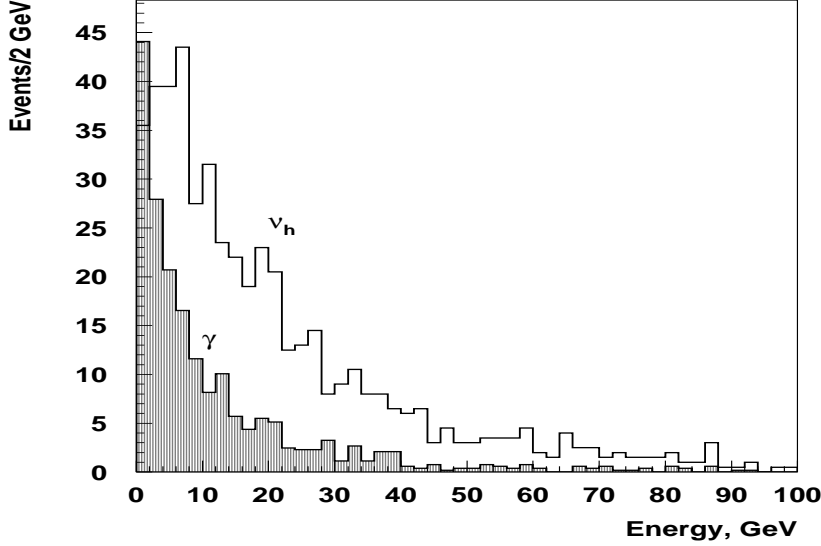


Fig. 3. Energy distributions of  $\nu_h$  neutrinos with the mass 50 MeV produced in the  $\nu_{\mu} NC$  interactions in the beam dump and pointing towards the NOMAD fiducial area, and photons from the  $\nu_h \rightarrow \gamma \nu$  decay in the NOMAD target. The spectra are normalized to a common maximum.

The NOMAD search for an excess of single photon events is described in detail in Ref. [24]. Briefly, it used data collected with of  $5.1 \times 10^{19}$  protons on target. The strategy of the analysis was to identify  $e^+ e^-$  candidates by reconstructing in the DC isolated  $e^+ e^-$  pairs with the total energy greater than 1.5 GeV and invariant mass below 100 MeV, that are accompanied by no other activity in the detector. The measured rate of  $e^+ e^-$  pairs was then compared to that expected from known sources. Two samples of signal photon candidate events were selected in NOMAD among the total number of  $1.44 \times 10^6$   $\nu_{\mu} CC$  reaction

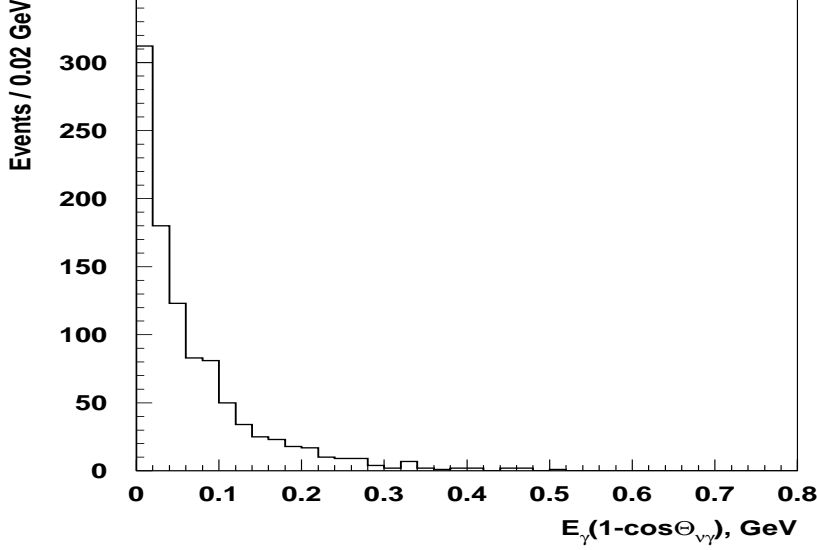


Fig. 4. Distribution of variable  $E_\gamma(1 - \cos\Theta_{\nu\gamma})$  for photons from the decay  $\nu_h \rightarrow \gamma\nu$  of the  $\nu_h$  with the mass 50 MeV produced in the  $\nu_\mu NC$  interactions in the SPS neutrino beam dump and decaying in the NOMAD fiducial volume.

recorded [24]. The first sample corresponds to photons emitted at any angle  $\Theta_{\nu\gamma}$  with respect to the primary neutrino beam direction, while the second one, corresponding to photons produced in the forward direction, was selected by using the cut  $\zeta < 0.05$  GeV on variable  $\zeta = E_\gamma(1 - \cos\Theta_{\nu\gamma})$ . After applying all selection criteria, 155 and 78 candidate events, with a predicted background of  $129.2 \pm 8.5 \pm 3.3$  and  $76.6 \pm 4.9 \pm 1.9$ , were observed in two regions, respectively. These results are found to be consistent with the background expectations and yield an excess of  $25.8 \pm 15.5$  and  $1.4 \pm 10.3$  events, respectively. The measured spectra are also found to be in good agreement with prediction. Hence, no evidence for an excess of single photons produced in  $\nu_\mu$  neutrino interactions has been observed and the corresponding upper limits of  $< 51$  events and  $< 18$  events at 90% CL for the number of single photon excess events in each sample were obtained, respectively.

Using Eq.(4) and these upper limits, we can then determine the 90% CL upper limit for the corresponding coupling  $\alpha_{\mu h}$ . The distribution of variable  $\zeta$  for decay photons in NOMAD is shown in Fig.4. As the  $\nu_h$ 's arrive at NOMAD from the source located at a relatively far average distance of  $\simeq 70$  m, most of the decay photons are produced in the forward direction, at a small values of  $\zeta$  and angle  $\Theta_{\nu\gamma}$ . In this case, the best bounds are obtained by selecting signal events with the cut  $\zeta < 0.05$  GeV. The corresponding 90% CL exclusion region in the  $\alpha_{\mu h}$  vs  $\tau_h$  plane shown in Fig. 5 together with the result obtained with the CHORUS target (see below) is calculated by using the relation  $N_{\nu_h \rightarrow \gamma\nu} < 18$  events. Our result is sensitive to a coupling  $\alpha_{\mu h} \gtrsim 10^{-3}$ , and corresponds

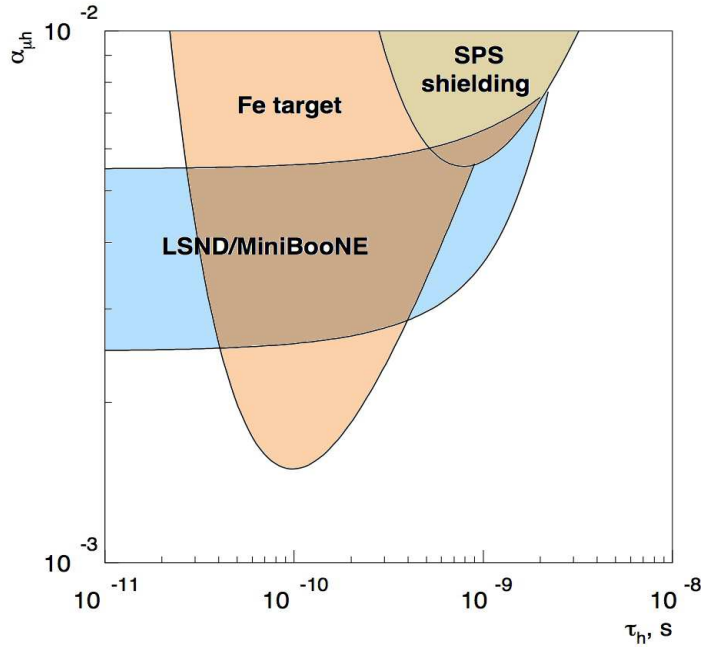


Fig. 5. The 90% CL exclusion regions in the  $(\tau_h, \alpha_{\mu h})$ - plane obtained from the NOMAD results [24] for the case of the  $\nu_h$  production in the SPS neutrino beam shielding and in the iron of the muon spectrometer of the CHORUS detector (Fe target). The area of the allowed LSND/MinibooNE parameter space corresponding to the  $\nu_h$  mass of 50 MeV is also shown.

to the  $\nu_h$  lifetime region  $\tau_h \simeq 10^{-10} - 10^{-9}$  s. Over most of this region, the  $\nu_h$  lifetime is sufficiently long, that  $Lm_h/p_h\tau_h \ll L'm_h/p_h\tau_h \ll 1$ .

For the  $\nu_h$  lifetimes shorter than  $\tau_h \simeq 10^{-9}$  s, new constraints on  $\nu_h$  properties can be obtained by considering the  $\nu_h$  production in the muon spectrometer matter (mainly iron) of the CHORUS detector located just about 10 m upstream of the NOMAD at the same neutrino beam line, as shown in Fig.1. The CHORUS detector, specifically designed to search for  $\nu_\mu - \nu_\tau$  oscillations at the SPS  $\nu_\mu$  neutrino beam, is a hybrid setup which combines a nuclear emulsion target with various electronic detectors such as trigger hodoscopes, a scintillating fibre tracker system, a hadron spectrometer, electromagnetic and hadronic calorimeters, and the muon spectrometer [30]. The muon spectrometer consists of seven tracking sections interleaved by six magnets. Each magnet is made from twenty iron disks, each of 3.75 m in diameter and 2.5 cm thick, with scintillator planes interspersed. The total weight of this Fe-target is about 260 t.

Similar to above considerations, the expected number of heavy neutrino  $\nu_h \rightarrow \gamma\nu$  decays in the fiducial volume of the NOMAD detector can be estimated by using expression (4), and taking into account the corresponding number of heavy neutrinos produced in the primary neutral current interaction in



the CHORUS iron target. In this estimate we required the  $\nu_h$  production to occur in the first three upstream sections of the CHORUS muon spectrometer, assuming that the hadronic showers from the neutrino interaction are completely absorbed in the remaining three downstream sections served as a "beam dump" with the total thickness of  $9 \lambda_{int}$ . This requirement is necessary to suppress background from  $K_L^0$  and  $n$  interactions discussed above, and also to avoid rejection of signal event by the NOMAD VETO system, when a secondary energetic hadron trigger the NOMAD veto counter V. The simulations show that due to the shorter distance to the Fe target the angular distribution of the decay photons converted in the NOMAD DC target is wider in comparison with the case, considered above, and the most restrictive limits are derived by using the NOMAD 90% CL upper limit of  $< 51$  events obtained for the case of the wider  $\zeta$  distribution of the single photon events.

The final 90% CL upper limit curves in the  $(\tau_h; \alpha_{\mu h})$  plane are shown in Fig. 5 together with the LSND-MiniBooNE  $\nu_h$  parameter space calculated for the  $\nu_h$  mass of 50 MeV. The attenuation of the  $\nu_h$  flux due to absorption in the shielding is found to be negligible. For example, our results can also be used to constrain the magnitude of the transition magnetic moment ( $\mu_h$ ) of the hypothetical  $\nu_h$ , see for more details Ref.[5]. The estimated attenuation of the  $\nu_h$  - flux due to  $\nu_h$  electromagnetic interactions with matter in this case is found to be negligible, since for the  $\nu_h$  lifetime in the range  $10^{-11} \lesssim \tau_h \lesssim 10^{-9}$  s, the  $\mu_h$  ranges from  $\simeq 10^{-8} \mu_B$  to  $\simeq 10^{-9} \mu_B$  (here  $\mu_B$  is the Bohr magneton), and the heavy neutrino mean free path in iron is more than 10 km, as compared with the iron and earth shielding total length of 0.4 km used in the SPS neutrino beam.

In summary, in this work we study possible manifestations of the radiative decays  $\nu_h \rightarrow \gamma \nu$  of a heavy sterile neutrino  $\nu_h$  in the CERN WANF neutrino beam. The existence of the  $\nu_h$  was proposed for the explanation of the anomalous excess events observed in the LSND and MiniBooNE experiments. It is assumed that  $\nu_h$ 's are dominantly produced in new  $\nu_\mu$ NC-like reactions in order to evade recent constraints from the  $\nu_h$  searches in reactions induced by  $\nu_\mu$ CC interactions. We study the  $\nu_h$  production occurring either in the CERN WANF neutrino beam line shielding, or in the iron of the muon spectrometer of the CHORUS detector located upstream of the NOMAD and followed by the radiative decay  $\nu_h \rightarrow \gamma \nu$  with the subsequent conversion of decay photons into  $e^+e^-$  pairs in the NOMAD active target. Using sensitive limits from the NOMAD experiment on single photon production in neutrino interactions, we derive new constraints on the  $\nu_h$  properties. The obtained results allow to exclude  $\nu_h$ 's of (1) for the lifetime values  $3 \times 10^{-11} \lesssim \tau_h \lesssim 5 \times 10^{-10}$  s, while still leaving open two bands for the existence of  $\nu_h$  with the lifetime either  $\tau_h \simeq 10^{-9}$  s or  $\tau_h \lesssim 3 \times 10^{-11}$  s. We have demonstrated a significant potential of the discussed experimental approach for the future more sensitive searches for the  $\nu_h$  at the high intensity neutrino facilities. For example, more restric-

tive constraints are expected to be obtained from the search for the  $\nu_h \rightarrow \gamma\nu$  decays from the  $\nu_h$  produced in  $\nu_\mu$  interactions in the future LAr experiment [21], aiming to check the origin of the LSND/MiniBooNE excess events at a neutrino facility at CERN [31,32].

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